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SOLAR DRYING OF TROPICAL HARDWOODS

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RESUMEN

La secadora solar es una estructura de madera cubierta con material plástico transparente que permite la transmisión de ondas de energía solar. Tiene abanicos que proveen la circulación del aire. La circulación del aire es controlada usando ventanas ajustables y atomizadores permiten el control adicional de la humedad relativa. En San Juan y Río Piedras la temperatura, la humedad relativa y la radiación solar son relativamente uniformes durante el año, siendo un poco más favorable para el secado rápido de la madera durante febrero y marzo.

Se determinó el tiempo requerido para secar madera en la secadora solar y al aire, de siete cargas de caoba hondureña de distintos gruesos y una carga mixta de 11 especies de maderas duras. La caoba de una pulgada de espesor con un contenido de humedad inicial de 50 por ciento puede ser secada en la secadora solar, bajando su contenido de humedad a 12 por ciento en 18 días; madera de 1-1/4 pulgadas requiere 25 días para secarse y la de 2 pulgadas aproximadamente 41 días. Las maderas duras mixtas de 1-1/4 pulgadas con peso específico que fluctua entre 0.48 y 0.82 requieren 43 días para secarse en la secadora solar, bajando de un promedio de contenido de humedad de 60 por ciento a 12 por ciento. Al final de las pruebas el contenido de humedad de las muestras varió solamente ± 2 por ciento del promedio. El uso de atomizadores para acondicionar la madera por 48 horas es adecuado para corregir los defectos de forzamiento. Un contenido de humedad de 15 por ciento puede alcanzarse en la secadora solar en la mitad o en la cuarta parte del tiempo requerido para secado al aire. No obstante, el alabeo y las rajaduras en la madera secada en la secadora solar no son más severos que los que surjen en réplicas secadas al aire.

SOLAR DRYING OF TROPICAL HARDWOODS

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SUMMARY

The lumber solar dryer is a wood-framed structure covered with thin transparent materials that permit transmission of shortwave solar energy. Baffled fans provide air circulation. Air exchange is regulated using adjustable vents and mist sprayers permit some additional control of relative humidity. At Río Piedras-San Juan, temperature, relative humidity, and solar radiation are fairly uniform throughout the year, being slightly more favorable for rapid lumber drying during February-March.

Solar and air drying time of seven charges of Honduras mahogany of varying thicknesses and one mixed charge of 11 hardwood species has been determined. From an initial green moisture content of 50 percent, 1-inch mahogany can be solar dried to a final moisture content of 12 percent in 18 days, 1-1/4-inch requires 25 days, and 2-inch stock about 41 days. The mixed hardwoods (1-1/4-inch), ranging in basic specific gravity from 0.48 to 0.82 required 43 days to solar-dry from an average green moisture content of 60 percent to a final average moisture content of 12 percent. At the end of the runs, moisture content of sample boards usually ranged ± 2 percent from this mean. A 48-hour mist spray conditioning treatment is adequate to remove severe casehardening. A moisture content of 15 percent can be reached in the solar dryer in one-half to one-fourth the time required for air drying. Nevertheless, warping and checking in the solar-dried lumber are no more severe than in matched air-dried material.

1/ In cooperation with the University of Puerto Rico.

INTRODUCTION

An experimental solar lumber dryer, located on the grounds of the Institute of Tropical Forestry at Río Piedras, was first put into operation in October 1961[1/]. Construction details and results of some early drying trials have been described by Peck (9, 10), and Maldonado and Peck (7). Briefly, the Río Piedras dryer, as well as others designed by the Forest Products Laboratory, consists of a wood-framed chamber covered with a double layer of transparent plastic film separated by an air space of about 1-5/8 inches. The wall facing north is sheathed with plywood. Baffled fans provide air circulation, and dampers or louvers permit control of air exchange through vents. A recorder is used to plot continuously the wet- and dry-bulb temperatures.

Temperature in the chamber varies with solar radiation intensity, reaching maximum values during the noon hours (on cloudless days) and rapidly approaching ambient temperatures at nightfall. Relative humidity can be controlled, somewhat, by adjusting the dampers or louvered openings of the vents, i.e. closing to maintain a higher relative humidity during the early stages of drying and opening fully for faster drying during the final stages. Solar drying of lumber, then, is a technique intermediate between air drying, where control of drying factors is at best casual, and kiln drying that permits a relatively sophisticated manipulation of temperature, humidity, and air movement.

The lumber solar dryer is essentially a non-focusing or flat-plate radiation collector. Maximum efficiency is obtained when the roof is tilted perpendicular to the mean position of the sun at noon or simply toward the equator at an angle with the horizontal equal to the latitude (3). Coverings of transparent plastic film or clear glass plates permit maximum transmission of shortwave solar energy into the chamber, and limit heat energy loss by reflecting inward longwave radiation (4).

This report describes solar drying trials of several thicknesses of mahogany (*Swietenia macrophylla* King) during various times of the year. Data from two previous tests (7) are included for comparison (charges 1 and 2). Also included are drying times and a rating of drying defects in a load of

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1/ In cooperation with the U.S. Forest Products Laboratory, at Madison, Wis.,and E.I. duPont de Nemours and Co., Inc., Wilmington, Del. E.C. Peck, of the Laboratory, designed the dryer and assisted G.H. Englerth, of the Institute, in planning the initial phases of this study. Dupont provided the plastic film.

mixed hardwoods, several species of which are refractory. Comparative data from air drying trials are also presented.

Data from these pilot studies are adequate for direct application to a small commercial operation using mahogany or other woods having similar drying properties. Results of the mixed hardwood trials indicate that solar drying is also feasible for species considered difficult to handle.

Insufficient information is available as to the optimum ratio between roof area and dryer volume, particularly under different climatic conditions. Until more design studies are made, a larger capacity can be obtained by lengthening the structure rather than modifying width or height dimensions. (The Río Piedras solar dryer is 10 feet wide by 20 feet long; the south wall is 9 feet 9 inches high and the north wall is 13 feet 4 inches.)

CLIMATIC CONDITIONS AT RIO PIEDRAS

Wind movement, air temperature, duration of rainfall, solar radiation, and relative humidity not only affect air drying, but also the efficiency of a solar dryer. Obviously, solar radiation intensity and duration are most important.

Table 1 presents climatological data for the Río Piedras-San Juan area (latitude 18°N., longitude 66°W.). Mean monthly temperatures are fairly uniform throughout the year, reaching maximum values of about 80°F. during May-November and dropping to 75°F. in January-February. Rainfall is uniform except for a relatively dry spell during February-March. Average daily relative humidity is also lowest at this time and is reflected in the low EMC (equilibrium moisture content) of 13 percent in March. The EMC is 14 to 15 percent throughout the rest of the year.

Solar radiation energy varies from 350 to 495 Langleys (gram calories per $cm.^2$) per day or a difference of extremes of only 145 Langleys. This range is quite narrow if compared to the following values presented by Bennett (2).

	December	March	June
Chicago	130	320	570
New York	150	350	550
Los Angeles	250	450	550
Phoenix	280	520	730
Miami	300	490	550
Río Piedras-San Juan	350	495	470

It is apparent that the availability of solar energy for wood drying at Río Piedras is fairly uniform throughout the year, being slightly more favorable during March, and slightly less intense during December, January, and February (table 1). In British units the solar heat varies from 1,290 to 1,825 Btu per foot^2 per day, with an average of 1,605 Btu per foot^2 (1 Btu per foot^2 = 0.271 cal. per cm.^{2}).

THE SOLAR DRYER

As originally designed, the solar dryer had a capacity of 2000 board feet (7) and was covered with a double layer of clear polyvinyl fluoride plastic film. The inner layer was 1 mil thick and the outer layer was 4 mils thick. One year after construction the solar dryer was increased in length to 20 feet, enlarging the capacity to about 3000 board feet. Due to mechanical failure, the 1-mil film was replaced with a stronger 2-mill gage.

By 1964, after only 2 years of service, there was considerable breakdown of the films in the roof panels. Most of the failures could be attributed to excessive flexing, but tears due to film embrittlement were also observed. The roof panels were removed and replaced with frames containing a single layer of double-strength window glass panes. Two small test panels with an improved framing were also mounted on the roof. One is covered with a single layer of 4-mil polyvinyl fluoride and the other with 5-mil weatherable polyester film. They are set out for continued exposure to determine serviceability under local conditions.

During the initial critical stages of solar drying green lumber, vents can be kept closed to maintain a high relative humidity. Peak solar radiation intensities during the noon hours, nevertheless, result in an excessive wet-bulb depression. Also, at the end of the drying schedule, stress sections invariably indicate severe casehardening. This defect was prevalent, as well, in the air-dried lumber. In conventional kilns, humidity control and stress relief are obtained with the aid of steam spray lines. It was believed that the lack of a steam source could be compensated for by the use of mist sprayers. Three small aperture nozzles and a water line were mounted along the base of the north wall (low pressure side.) With the water supply turned on and fans in operation, the mist is sucked up to the roof and then blown through the lumber courses. Instead of spraying cool tap water, more effective hot water can be made available by preheating in a simple solar water heater. The enlarged dryer and attached solar water heater are shown in figure 1.

A typical weekly pattern of dry- and wet-bulb temperatures in the solar dryer (vents open, mist sprayers off) is shown in figure 2. Peak temperatures and maximum wet-bulb depressions are reached during the noon hours and opposite extremes occur at night. Table 2 compares temperature, relative humidity, and resultant EMC conditions inside and outside the solar dryer for several periods. Also shown is the effect of mist spraying with the vents closed.

The maximum temperature within the dryer averages 114°F., whereas the mean maximum ambient temperature is 86°F., a difference of 28°F. Average temperature within and outside the dryer compares with that measured by Peck (9) during June-September in the Madison experimental solar dryer. However, during the winter months (November-February) average Madison dryer temperature dropped considerably, e.g. 33°F. in December in contrast to 97°F. in September. Average relative humidities outside the solar dryer during December 1963 and July 1965 are lower than those recorded for this area in table 1 and subsequently so are the EMCs, about 13 percent as compared to a long-term mean of 15 percent. Average EMC within the solar dryer ranges from 8.0 to 10.5 percent.

With vents open and mist sprayers off, the mean minimum EMC for different periods is 6.2 percent as compared to 11.5 percent when the vents are closed and sprayers in operation. Average EMC values with and without humidification are 16.0 and 9.6 percent respectively. Mean maximum dry-bulb temperature is reduced when mist sprayers are on: 102°F. as compared to an average of 114°F.

SOLAR DRYING OF MAHOGANY

Hardwood lumber imports into Puerto Rico in 1964 amounted to some 8 million board feet, of which 73 percent was mahogany, 14 percent related Cedrela species, and 13 percent other hardwoods. The prevalent use of mahogany (primarily for furniture and millwork) and its availability in an almost green condition suggested an initial emphasis on this species for drying trials. The present practice in most local woodworking plants is to either convert green lumber into furniture components or to follow indifferent air-drying procedures. Fortunately, the very low shrinkage values of mahogany permit some toleration of this abuse.

The mahogany boards selected for these drying studies were from current shipments received from Mexico by lumber dealers in the San Juan area. Initial green or partially air-dried moisture content varied from about 30 to 60 percent. For

each charge the solar dryer was loaded to capacity or near capacity, i.e. 2000 board feet for the original design and about 3000 board feet in the enlarged chamber. All loads consisted of random widths and lengths and were box piled using 3/4-inch thick stickers. Sample boards were used to determine current and final moisture content. Except for the December 1961 trial, air drying piles of matched material were set out to obtain comparative data. Temperature and relative humidity were recorded both inside and outside the solar dryer.

Equilibrium moisture content in the Río Piedras-San Juan area ranges from 13 to 15 percent throughout the year, averaging about 14.5 percent. Air conditioning is now common in commercial buildings and in many homes, resulting in a low EMC of about 9 percent. A desirable final moisture content of lumber for interior use should be between these extremes, or 11 to 13 percent. Reaching this final moisture content range was an objective of the various solar drying trials. However, for comparison of air and solar drying time, a final moisture content of 15 percent was also selected. This value can be reached eventually by continuing the air drying trials for an extended period of time. Rather than delay the return of the test material to cooperating suppliers, the number of days needed to reach this moisture content was estimated by extrapolating the air drying curves. Air drying rates slow down appreciably as lumber approaches EMC. The use of a straight line trend from the latest rate measured, then, results in a slight underestimate of air drying time.

The mahogany drying trials consisted of three charges of 1-inch boards, one charge of 1-1/4 inch thick stock, and three charges of 2-inch lumber. Drying time for these seven charges are shown in table 4. Additional data follow:

1-inch Thick Lumber

Started December 15, 1961 (charge 2)

Charge 2 lumber had an average moisture content of 35 percent when loaded for solar drying. A matched air-dry pile was not available for this test. After 25 days in the solar dryer, average moisture content of sample boards was 11 percent, ranging from 8 to 12 percent. Only 14 days of solar drying were required to obtain an average moisture content of 15 percent (table 4).

Started August 5, 1963 (charge 5)

The boards loaded in the solar dryer for this run had an initial moisture content of 28 percent. Moisture content of

the lumber set out for air drying was only 23 percent. After 12 days in the solar dryer, average moisture content of sample boards was 11 percent, ranging from 10 to 12 percent. Shell and core moisture content determinations showed differences of not more than one percent. Stress sections were also prepared, as described by McMillen (8), and showed severe casehardening present in all of the material. For the same 12-day period, air drying sample boards had a moisture content of 17 percent. About 16 days would have been required to air-dry these boards to a moisture content of 15 percent (extrapolated) as compared to only 6 days by solar drying (table 4).

In previous solar dryer charges, weighings of sample boards were used to calculate moisture content variation between but not within boards. As an additional evaluation of drying uniformity, shell and core differences were determined for this and subsequent runs (charges 6, 7, and 8).

Started December 17, 1963 (charge 7)

Initial moisture content of the boards in the solar dryer was 48 percent (figure 3). Sample boards in the air drying piles had an initial moisture content of 39 percent. After 16 days in the chamber, the average moisture content was 13 percent, ranging from 11 to 14 percent. Severe casehardening was present; but after 48 hours of mist spray, this defect was eliminated (sprayers had been installed before the start of charge 6.) Moisture content differences between shell and core were less than 1 percent. After this same 16 days, the average moisture content of air drying sample boards was 20 percent. An additional drying time of 6 days dropped this value to 19 percent. Again by extrapolation, it would have required at least 40 days for the air drying boards to reach a moisture content of 15 percent. In the solar dryer this moisture content was reached in only 10 days (table 4).

1-1/4-inch Thick Lumber

Started October 26, 1961 (charge 1)

Lumber in this charge had an average initial moisture content of about 50 percent. Boards in the solar dryer reached a moisture content of 11 percent after 30 days. Differences between the wettest and driest sample boards were no greater than 2 percent. After this same 30-day period the average moisture content of the air drying lumber was 25 percent. An average moisture content of 15 percent was reached in the solar dryer after 19 days. By extrapolation of the air drying data, we can estimate that about 70 days would have been required to reach this same moisture content (table 4).

2-inch Thick Lumber

Started January 16, 1962 (charge 3)

The lumber used in this run had an average initial moisture content of about 40 percent. Stock in the solar dryer reached a final moisture content of 12 percent in 35 days. Moisture content of the sample boards varied by only ± 1 percent from this mean. For this same period, the matched air drying pile had an average moisture content of 23 percent. Twenty-seven days were required to solar dry to a moisture content of 15 percent as compared to at least 80 days (by extrapolation) that would be needed in air drying (table 4).

Started February 7, 1963 (charge 4)

Before the start of this run, the solar dryer was enlarged as already described, to a capacity of about 3000 board feet and recovered with plastic films. Originally there were four 16-inch fans provided for air circulation. The rebuilt dryer had 9 fans. Air velocity through the piles ranged from 65 to 100 feet per minute.

This run had an initial moisture content of 60 percent. After 39 days of solar drying, the lumber reached a moisture content of 14 percent. Sample boards showed a larger variation in moisture content than in previous trials, ranging from 11 to 18 percent. Toward the end of the run sample boards were losing moisture at the rate of 0.4 percent per day. On this basis of moisture loss about 45 days would have been required to solar dry the lumber to 12 percent. An estimated 90 percent of the boards would have deviated from this mean by only ± 2 percent. At the end of the 39-day period, the air drying lumber reached a moisture content of 27 percent. By extrapolation we can estimate that not less than 100 days would be required to reach a moisture content of 15 percent as compared to only 37 days required in the solar dryer (table 4).

Started September 8, 1963 (charge 6)

Prior to the start of this run, the three mist sprayers previously described were installed but used only for conditioning at the end of the run. Initial moisture content of solar dryer sample boards was 47 percent as compared to a moisture content of 41 percent for the air drying material (figure 3). Forty days of solar drying were required to reach an average moisture content of 12 percent. The charge was kept in the solar dryer an additional 4 days for mist spray conditioning (this included shutdown time for tests to determine degree of stress relief.) At the end of this 4-day period the average moisture content was 11 percent, ranging from 8

to 13 percent. Differences in moisture content between shells and cores were not more than 1 percent. Severe casehardening was present as indicated by the conventional prong test (8); but after 48 hours of mist spray with vents closed, stress relief was complete. During the same 40-day period the air drying sample boards reached an average moisture content of 20 percent. It is estimated that the air drying material would have reached an average moisture content of 15 percent in not less than 80 days, compared with 31 days in the solar dryer (table 4).

A summary of the mahogany drying time, as well as data on charge 8 described below, is given in table 3. Drying curves for the three test trials of 2-inch mahogany lumber (charges 3, 4, and 6) are shown in figure 4. Deviations between seasons are negligible. This clearly demonstrates that the almost constant level of solar energy available throughout the year at Río Piedras can be uniformly utilized to dry wood in a dryer of this design. Possibilities of developing time schedules to simplify solar drying operations, then, are highly favorable.

Figure 5 compares the solar drying time of the three mahogany thicknesses evaluated. The 1-inch and 2-inch curves are each composites of the three drying charges (portions have been extrapolated). Within these limits, it appears that solar drying time varies almost directly with thickness. Relative drying times of these thicknesses to 12 percent moisture content are in fairly close agreement with kiln drying experience reported by Higgins (5). Our time ratio for 1-, 1-1/4-, and 2-inch lumber is 44:66:100; Higgins' values are 40:55:100.

SOLAR DRYING OF MIXED HARDWOODS

Started April 19, 1965 (charge 8)

About 5000 board feet of 1-1/4-inch lumber, 6 feet long, of random widths, and representing 11 species native to the area were available for this phase of the study. Of this mixed green-from-the-saw material, 2000 board feet were loaded in the solar dryer and the balance was set out for air drying. Sample boards representing each species were located on opposite sides of the piles. Following is a list of the species in order of increasing specific gravity:

Puerto Rican Common name	Scientific Name	Specific[1/] Gravity
Guaraguao	_Guarea trichilioides_ L.	.48
Roble blanco	_Tabebuia heterophylla_ (DC.) Britton	.54
María	_Calophyllum brasiliense_ Camb.	.56
Laurel sabino	_Magnolia splendens_ Urban	.57
Guamá	_Inga laurina_ (Sw.) Willd.	.57
Granadillo	_Buchenavia capitata_ (Vahl) Eichl.	.62
Maricao	_Byrsonima coriacea_ (Sw.) DC.	.63
Algarrobo	_Hymenaea courbaril_ L.	.73
Moca	_Andira inermis_ (W.Wright) H.B.K.	.74
Ausubo	_Manilkara bidentata_ (A.DC.) Chev.	.80
Motillo	_Sloanea berteriana_ Choisy	.82

1/ Based on green volume and oven-dry weight.

Volumetric shrinkage from the green to oven-dry condition varies considerably for these species, e.g. 9 percent for granadillo and 16 percent for ausubo. Air seasoning characteristics as well as other physical properties of these woods have been described by Longwood (6).

The solar dryer, at this time, was roofed with panes of double strength window glass (except for the two test panels covered with plastic films) and had a water supply to the mist sprayers that could be preheated in a solar water heater.

At the start of the solar dryer run, the vents were closed and the mist sprayers were turned on during daylight hours in order to obtain a small wet-bulb depression. This condition was maintained for 20 days at which time the wettest sample boards had reached a moisture content of 30 percent. Vents were then adjusted to their maximum opening and the mist sprayers were shut off until the end of the run.

Drying curves showing moisture content of the wettest and driest sample boards, as well as averages for all species combined for both air and solar drying, are presented in figure 6. To facilitate comparison, drying times are also tabulated in table 4. Initial green moisture content varied from 38 to 80 percent. After 43 days in the solar dryer, the average moisture content was 12 percent, ranging from 11 to 14 percent. Severe casehardening was present in all species. A conditioning period of 48 hours (mist sprayers on, vents closed) resulted in stress-free boards in all cases except for slight residual stress in motillo and moca (figure 7). Maximum differences between shell and core moisture content was 4 percent ... 15 of the 22 sample boards had differences of not more than 2 percent.

At the end of this same 43-day drying period, average moisture content of the air-dried sample boards was 20 percent, ranging from 18 to 26 percent. Air drying was continued for an additional 31 days, at which time the moisture content varied from 15 to 19 percent, averaging 17 percent. The 74 days of air drying to reach this moisture content level compares with the 35 days required in the solar dryer. After air drying, the lumber was loaded in the solar dryer and brought down to a moisture content of 12 percent in 12 days - a total drying time of 86 days. The load was kept in the solar dryer an additional 9 days and the final moisture content was 10 percent, ranging from 8 to 12 percent. As for the material dried green-from-the-saw, a 48-hour conditioning period removed almost completely the severe casehardening that was present.

This discussion has been mainly concerned with average drying time of loads of mixed species having different drying properties. Normal commercial practice usually dictates the separation of boards according to species, heartwood or sapwood, moisture content, and thickness. Sample boards in the solar dryer showed that some species reached a moisture content of 30 percent after 7 to 9 days while others required about 20 days to dry to this level. If this material were sorted and treated separately according to drying properties, we should expect the time to solar dry 5/4-inch hardwoods, from a green condition to a final moisture content of 12 percent, to range from 35 to 45 days.

COMPARISON OF DRYING DEFECTS IN AIR- AND SOLAR-DRIED LUMBER

1. Mahogany (*Swietenia macrophylla*)

This well known timber dries fairly rapidly without much checking and warping and once dried has small movement with humidity changes (1). Radial, tangential, and volumetric shrinkages from the green to the oven-dry condition are respectively 3.5, 4.8, and 7.7 percent (12). These excellent physical properties make this species one in which a great deal of degrade would not be expected. Nevertheless, solar drying of mahogany in less than half the time required for air drying without humidity control does suggest the possibility of some loss in grade due to surface checking, cup, bow, etc. The 2-inch thick lumber used in charge 6 was inspected to determine whether or not such losses should be anticipated.

During the early stages of drying, temperature and relative humidity conditions in the solar dryer may be harsher than those called for in an appropriate kiln drying schedule (11). At green moisture contents of 40 percent or higher the recommended schedule for 2-inch mahogany designates a dry-bulb temperature of 110°F., and an EMC of 16 percent. During the

first week of solar drying charge 6, noon-hour temperature averaged 118°F. while the average EMC was about 8 percent (vents open, mist sprayers off). In the kiln schedule these conditions are established only when the wettest sample boards have reached a moisture content of 30 percent.

Before and after drying, each board was examined for amount and extent of surface and end checking as well as degree of warp classifiable as cup, bow, crook, and twist. Each defect was rated as follows: 1 - absent; 2 - slight; 3 - moderate; 4 - severe. A total of 105 solar-dried and 74 air-dried boards were inspected. The percentages of boards having moderate to severe warping and checking are given below:

Defect	Solar-dried Pct.	Air-dried Pct.
Checks		
surface	4	1
end	19	22
Warp		
cup	11	12
bow	13	8
crook	25	4
twist	1	0

A statistical analysis of all the data, including the percentage of boards rated "1" and "2", shows that only bow and crook in the solar-dried material, is significantly greater at the 5 percent level.

This direct comparison must be qualified. At the time of inspection the solar-dried boards had an average moisture content of 11 percent while the air-dried stock had an average moisture content of 20 percent. If we assume a fiber saturation point of 24 percent, then about half of the possible total shrinkage to an oven-dry condition has taken place in the solar-dried material. The air-dried lumber had undergone less than one-fourth of the total shrinkage. Upon further air drying we should expect a substantial increase in distortion or warp and possibly some additional checking.

Since 4 of the 6 defects evaluated were not significantly different, and in view of the higher moisture content of the air-dried lumber, we may conclude that accelerated solar drying of non-refractory species, such as mahogany, need not result in higher degrade as compared to air drying.

2. Mixed hardwoods

The 11 species used in the mixed load that was solar-dried green-from-the-saw in charge 8, were also inspected for drying defects. A comparison is made with the material that was first air-dried and then solar-dried.

Drying and shrinkage properties of these species vary considerably. According to Longwood (6), maría and algarrobo are particularly prone to degrade while ausubo, granadillo, and laurel sabino dry relatively defect-free.

The procedures described for the mahogany study were used. Green boards set aside for air drying were not marked to show end splits already present due to shake in the logs. Since it is not always possible to differentiate between end checks caused by drying and end splits not related to seasoning, this defect was not measured.

The mixed species were solar dried from a green condition to a final average moisture content of 12 percent in 43 days. The comparative material was air-dried to a moisture content of 17 percent in 74 days and then solar-dried for an additional 21 days to a final average moisture content of 10 percent. Though there is a difference in final moisture content, it is believed that no serious errors will arise if direct comparisons of drying defects are made.

Results for both lots of material are summarized in table 5. The solar-dried boards, as a group, had significantly less warp than those boards that were initially air-dried. However, there were no significant differences in surface checking.

Regardless of the drying method, roble blanco, guamá, granadillo, laurel sabino, and guaraguao may be rated as relatively free of warping and checking. This listing is somewhat different from that given by Longwood (5). His material was air-dried under an open shed for 15 to 31 weeks to a final moisture content of 16 to 19 percent. The boards in this study were air-dried to about the same moisture content in only 10 weeks, but were evaluated only after solar-dried to a moisture content of 8 to 12 percent.

CONCLUSIONS

Solar and air drying time of seven charges of Honduras mahogany (Swietenia macrophylla) of varying thicknesses and one mixed charge of more refractory hardwoods (1-1/4 inch thick) were determined. Comparisons of drying defects were also made. From the results to date, the following conclusions can be drawn:

1. Solar drying curves of mahogany show that the number of days required to reach a desired final moisture content varies little with time of year.

2. Mean maximum temperature within the solar dryer averages about 114°F. as compared to a mean maximum ambient temperature of 86°F. Average relative humidity is about 55 percent and 76 percent respectively inside and outside the chamber. Equilibrium moisture content in the solar dryer averages about 10 percent in contrast to over 13 percent for outside conditions.

3. Under local climatic conditions a moisture content of 12 percent is readily obtainable in a solar dryer and a final moisture content of 10 percent is possible. Individual board variation from these final values is seldom greater that ± 2 percent. Differences between shell and core moisture content are at this same low level.

4. Assuming an initial moisture content of 50 percent, 1-inch mahogany can be solar-dried to a final moisture content of 12 percent in 18 days, 1-1/4-inch requires 25 days, and 2-inch stock about 41 days. If the mahogany lumber is first air-dried for 1 to 4 weeks to a moisture content of 30 percent, then time in the solar dryer could be reduced to 13, 19, and 29 days respectively.

5. Drying time for a mixed load of 1-1/4-inch hardwood lumber was 43 days (green to a moisture content of 12 percent.) If each species could have been handled separately, drying time would have varied from 35 to 45 days.

6. Depending on the thickness of the lumber, a moisture content of 15 percent can be reached in the solar dryer in one-half to one-fourth the time required for air-drying.

7. Except for bow and crook, 2-inch mahogany boards solar-dried to a final moisture content of 11 percent had the same amount of drying defects as matched lumber air-dried to a moisture content of 20 percent. Mixed hardwood species solar-dried green-from-the-saw had significantly less warp than matched air-dried stock (air-dried to a moisture content of 17 percent and then solar-dried to a final moisture content of 10 percent.) There were no significant differences in degree of surface checking.

8. Low-cost and easy-to-install mist sprayers permit humidity control during the critical early stages of solar drying and are also very effective in conditioning to remove casehardening.

Table 1.--Mean monthly climatological data for the Río Piedras - San Juan area (1900-1964)

Item	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Mean Annual
Temperature (°F.)	75.1	75.1	76.0	77.0	78.8	79.9	80.1	80.8	80.7	80.2	78.6	76.7	78.3
Relative Humidity (Pct.)	75	74	72	75	76	78	78	77	78	78	77	75	76
Equilibrium Moisture Content (Pct.)	14	14	13	14	14	15	15	15	15	15	15	15	14.5
Rainfall (in.)	4.13	2.70	2.07	3.89	7.16	5.83	6.02	6.34	6.04	5.24	6.05	4.89	60.36
Solar Radiation (Langleys)1/	385	440	495	480	460	470	480	460	410	410	375	350	435

1/ Mean daily for years 1957 - 1960. Data supplied by M. del C. Fernández, University of Puerto Rico, Agricultural Experiment Station, Río Piedras.

Table 2.--Temperature, relative humidity, and EMC (equilibrium moisture content) for selected periods inside and outside the solar dryer

Item	December 1963 Inside	December 1963 Outside1/	July 1965 Inside	July 1965 Outside1/	April 1965 Mist Sprayers on2/
Temperature (°F.)					
Mean maximum	110	86	109	86	102
Mean minimum	73	68	78	75	72
Average	91	77	94	80	87
Relative Humidity (Pct.)					
Mean maximum	69	86	69	81	90
Mean minimum	48	43	41	55	66
Average	58	64	55	68	78
Equilibrium Moisture Content (Pct.)					
Mean maximum	13.0	18.8	12.7	16.6	21.0
Mean minimum	8.0	8.0	6.9	9.8	11.5
Average	10.5	13.4	9.8	13.2	16.3

1/ Measured in the shade outside the solar dryer.
2/ Vents closed and mist sprayers on during daylight hours.

Table 3.--Drying time and final moisture content of various charges of solar- and air-dried lumber

Lumber Thickness	Starting Date	Initial Moisture Content	Drying Days	Solar Drying		Air Drying	
				Final Moisture Content	Range	Final Moisture Content	Range
in.		Pct.	No.	Pct.	Pct.	Pct.	Pct.
			MAHOGANY (SWIETENIA MACROPHYLLA)				
1	Dec. 15, 1961 (charge 2)	35	25	11	8-12	--	--
	Aug. 5, 1963 (charge 5)	28	12	11	10-12	17	16-18
	Dec. 17, 1963 (charge 7)	48	16	13	11-14	20	19-23
1-1/4	Oct. 26, 1961 (charge 1)	50	30	11	10-12	25	23-27
2	Jan. 16, 1962 (charge 3)	40	35	12	11-13	23	20-28
	Feb. 7, 1963 (charge 4)	60	39	14	11-18	27	20-35
	Sept. 8, 1963 (charge 6)	47	44	11	8-13	20	17-25
			MIXED PUERTO RICAN HARDWOODS (11 SPECIES)				
1-1/4	Apr. 19, 1965 (charge 8)	38-80	43	12	11-14	20	18-26

Table 4.--Solar and air drying times for various thicknesses of mahogany and mixed Puerto Rican Hardwoods

Drying Trials	Days Required to Dry Between Various Moisture Content Levels[1]						
	60 to 50 Pct.	50 to 40 Pct.	40 to 30 Pct.	30 to 20 Pct.	20 to 15 Pct.	15 to 12 Pct.	50 to 15 Pct.
MAHOGANY (SWIETENIA MACROPHYLLA)							
1-inch							
Solar-dried							
Dec. 1961 (charge 2)		-	(4)	6	6	5	
Aug. 1963 (charge 5)		-	-	(3)	4	3	
Dec. 1963 (charge 7)		2	3	3	3	6	
Average		2	3	4	4	5	13
Air-dried							
Dec. 1961 (charge 2)		-	-	-	-		
Aug. 1963 (charge 5)		-	-	(6)	(14)		
Dec. 1963 (charge 7)		(2)	3	11	(26)		
Average		2	3	8	20		33
1-1/4-inch							
Solar-dried							
Oct. 1961 (charge 1)	(2)	3	3	7	6	6	19
Air-dried							
Oct. 1961 (charge 1)	-	7	13	(20)	(30)	-	70
2-inch							
Solar-dried							
Jan. 1962 (charge 3)	-	-	7	10	10	8	
Feb. 1963 (charge 4)	4	5	7	11	10	(8)	
Sept.1963 (charge 6)	-	4	8	11	9	8	
Average	4	5	7	11	10	8	33
Air-dried							
Jan. 1962 (charge 3)	-	-	13	(30)	(40)		
Feb. 1963 (charge 4)	5	8	15	(33)	(45)		
Sept.1963 (charge 6)	-	5	13	(27)	(40)		
Average	5	7	14	30	42		93
MIXED PUERTO RICAN HARDWOODS							
1-1/4-inch							
Solar-dried							
Apr. 1965 (charge 8)	4	5	7	12	11	4	35
Air-dried							
Apr. 1965 (charge 8)	3	4	7	29	50	-	90

1/ Values in parenthesis are estimates based on extrapolation.

Table 5.--Percentage of 1-1/4-inch boards having moderate to severe drying defects

Puerto Rican and Scientific Names	Solar Drying 1/						Air Drying 2/				
	Warp				Checking		Warp				Surface
	Cup	Bow	Crook	Twist	Surface	End	Cup	Bow	Crook	Twist	Checking
Algarrobo (*Hymenaea courbaril*)	14	28	35	7	28	0	65	20	32	64	12
Ausubo (*Manilkara bidentata*)	0	0	0	4	13	13	16	8	6	28	36
Granadillo (*Buchenavia capitata*)	0	4	7	0	0	11	10	19	14	23	2
Guamá (*Inga laurina*)	0	0	0	6	0	0	8	17	20	25	0
Guaraguao (*Guarea trichilioides*)	0	8	0	0	8	4	11	21	26	21	0
Laurel sabino (*Magnolia splendens*)	0	0	0	7	5	0	25	9	15	28	3
María (*Calophyllum brasiliense*)	0	20	13	33	17	7	36	18	35	62	3
Maricao (*Byrsonima coriacea*)	13	13	13	7	13	7	36	32	8	40	12
Moca (*Andira inermis*)	0	12	0	0	20	12	42	34	24	22	4
Motillo (*Sloanea berteriana*)	0	0	0	12	8	28	28	7	7	41	42
Roble blanco (*Tabebuia heterophylla*)	0	0	0	0	0	0	3	6	6	11	0

1/ Dried green-from-saw to final moisture content of 12 percent.
2/ Air-dried green-from-saw to 17 percent moisture content, then solar-dried to final moisture content of 10 percent.

Figure 1.--The enlarged solar dryer. Roof is covered with a single layer of double-strength glass. Walls are sheathed with a double layer of polyvinyl fluoride plastic film. Note solar water heater in the foreground.

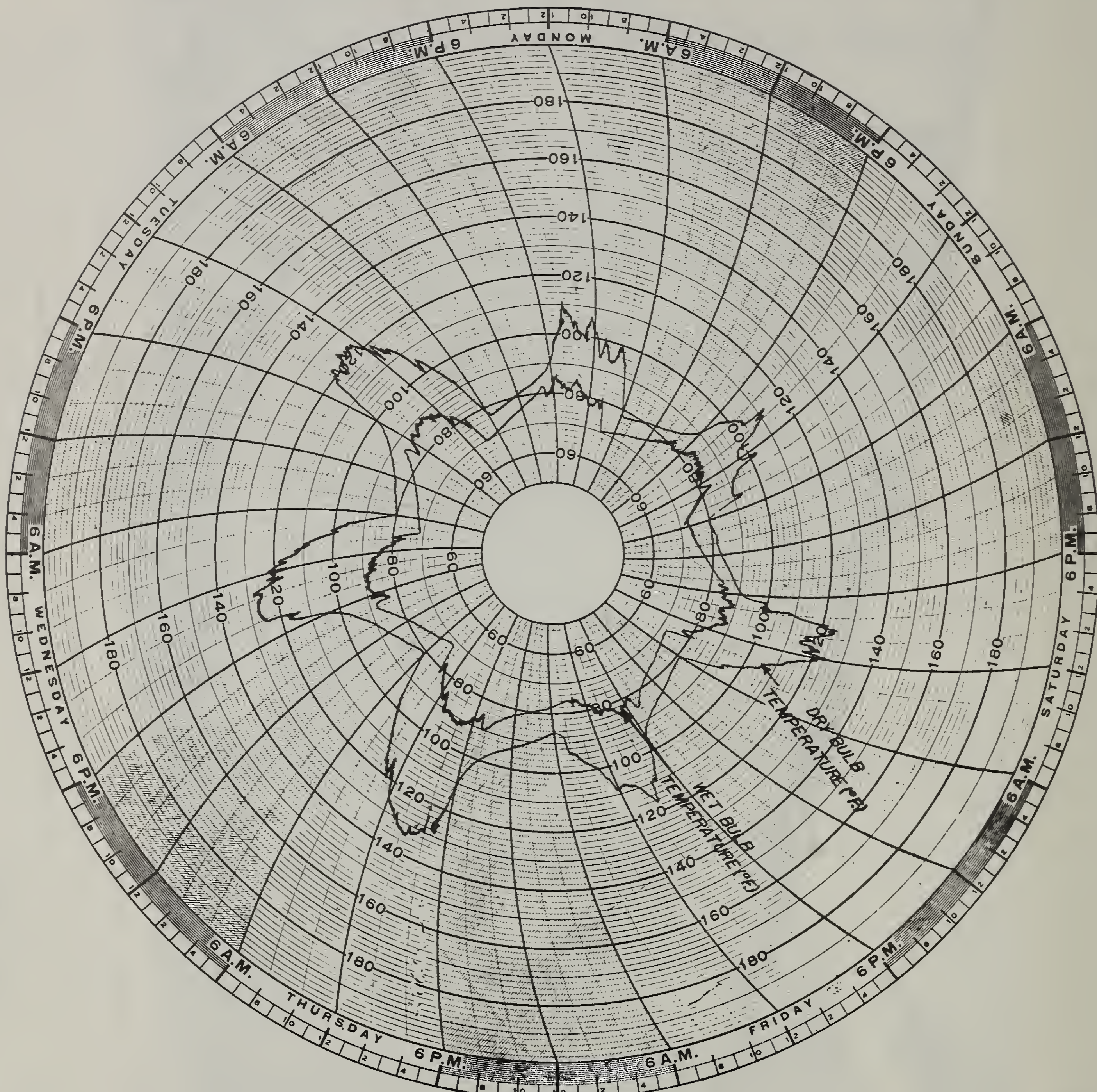

Figure 2.--Typical weekly pattern of dry- and wet-bulb temperatures in the solar dryer. Maximum values occur during the noon hours.

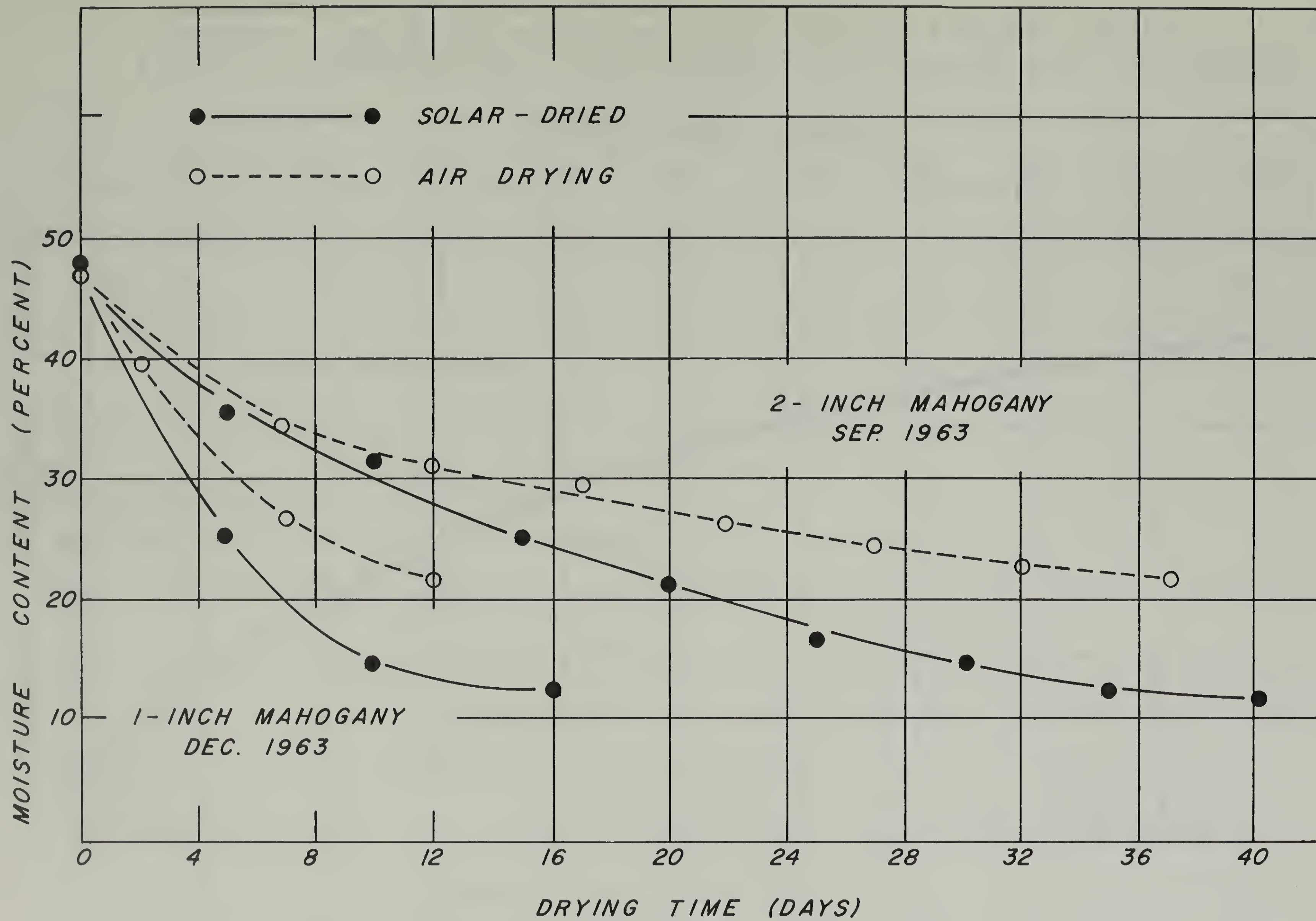

Figure 3.--Comparison of drying curves for solar- and air-dried mahogany using 1- and 2-inch lumber. Air drying curves have been extrapolated to the same initial green moisture content.

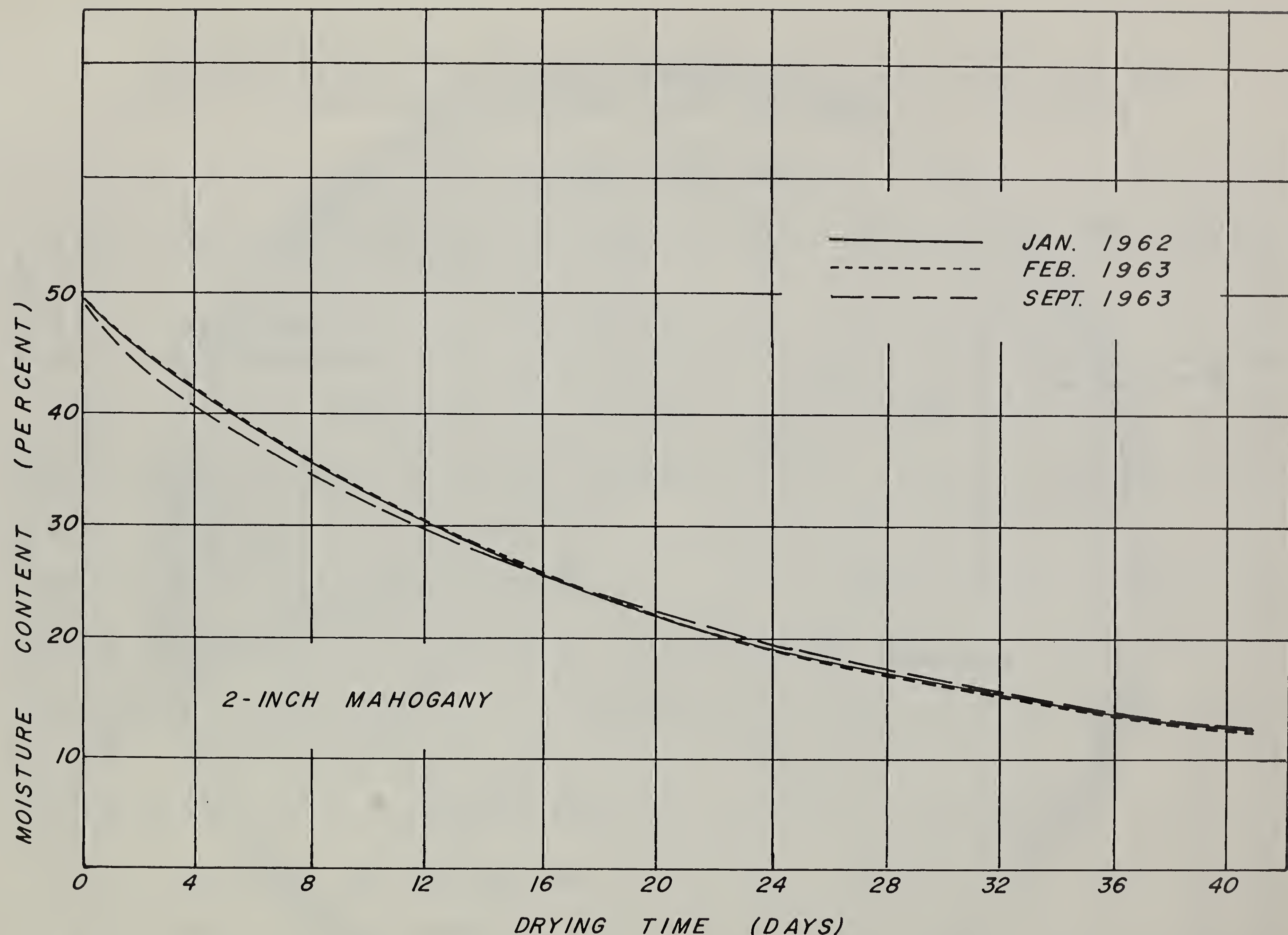

Figure 4.--Comparison of 2-inch mahogany solar drying time for various seasons. Two points to the 50 and 12 percent moisture content extremes have been extrapolated.

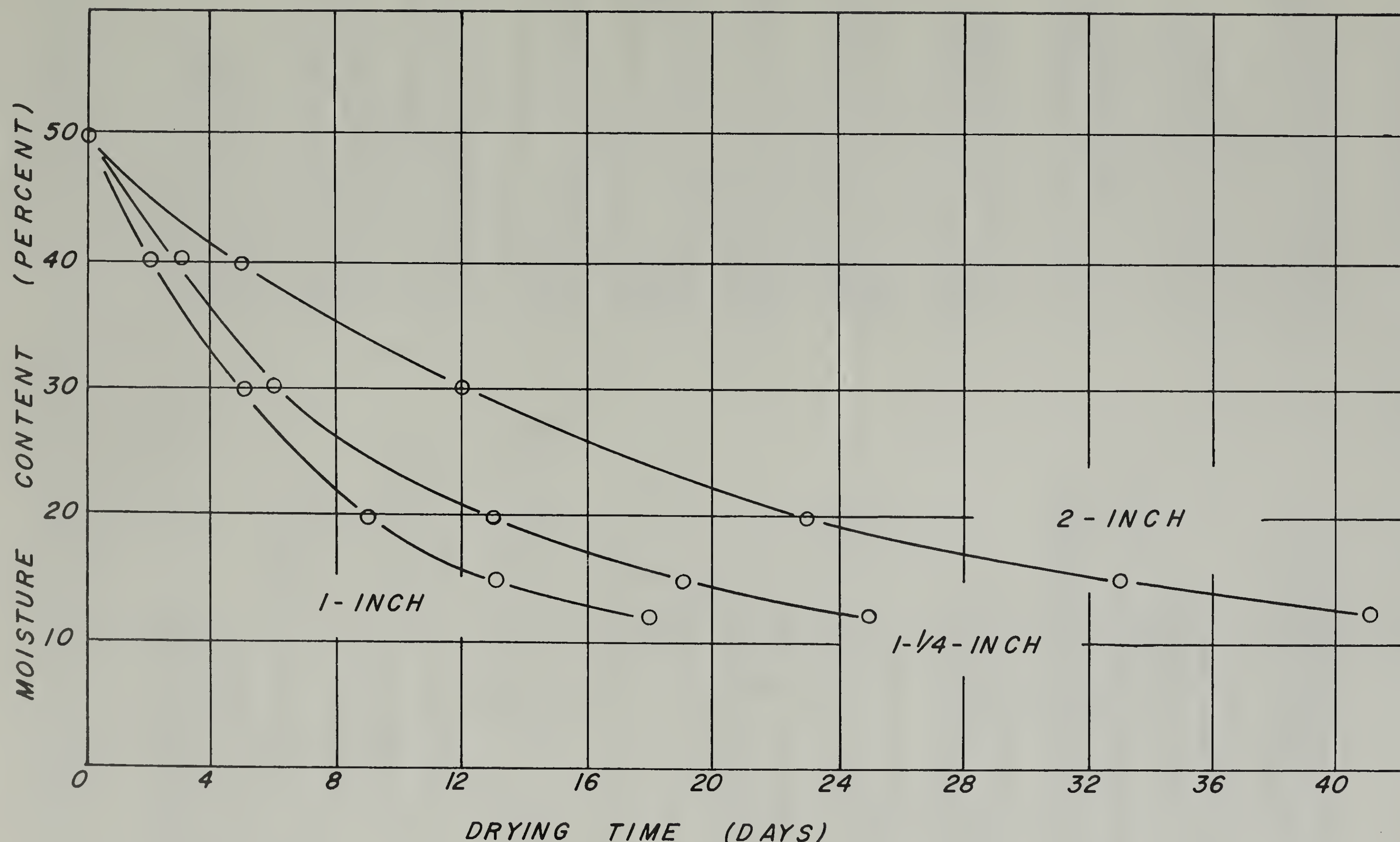

Figure 5.--Comparison of solar drying time for several thicknesses of mahogany. The 1-inch and 2-inch curves are composites of 3 drying charges.

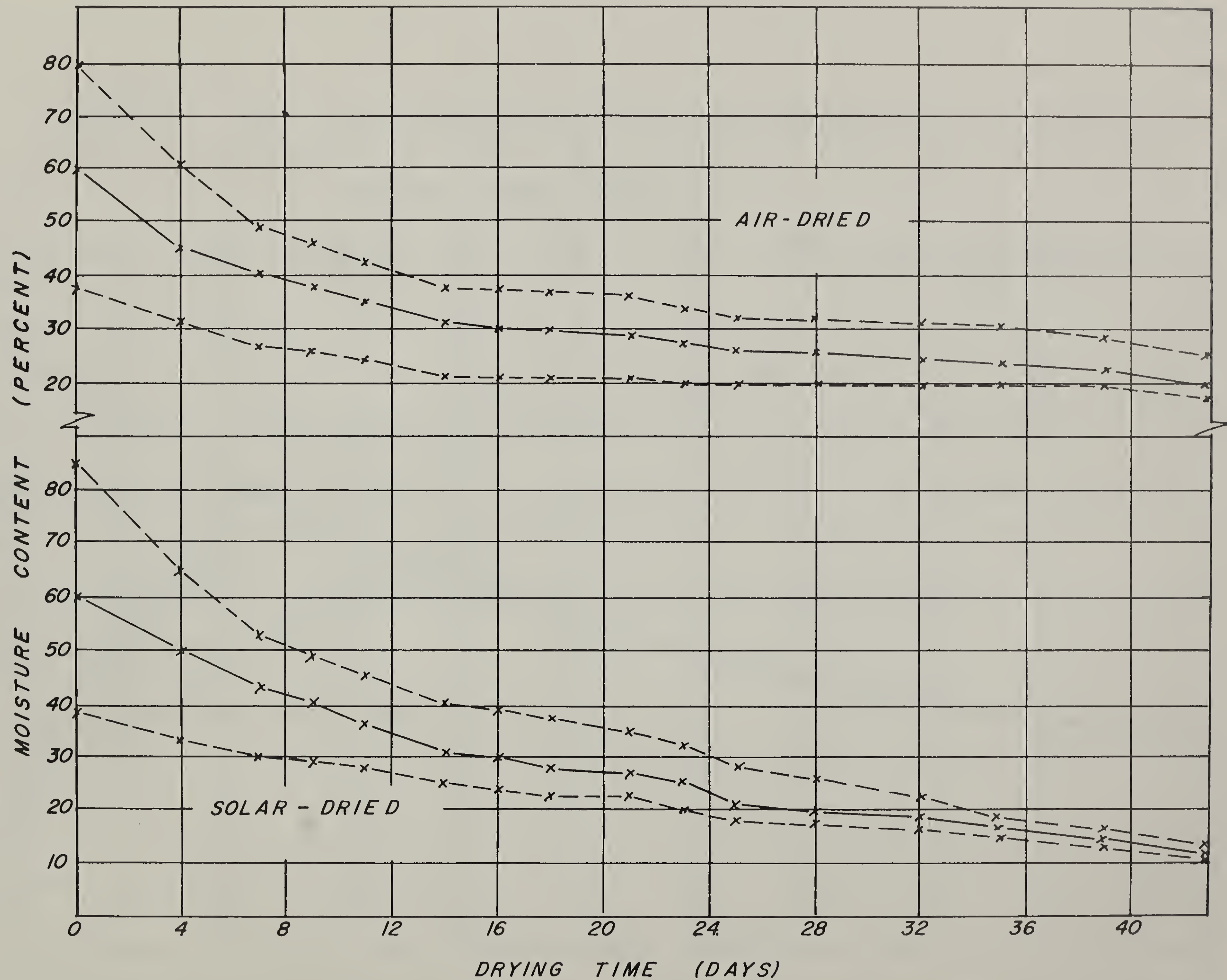

Figure 6.--Comparison of air and solar drying curves for 1-1/4-inch mixed hardwoods. Moisture contents of average, wettest, and driest sample boards are plotted.

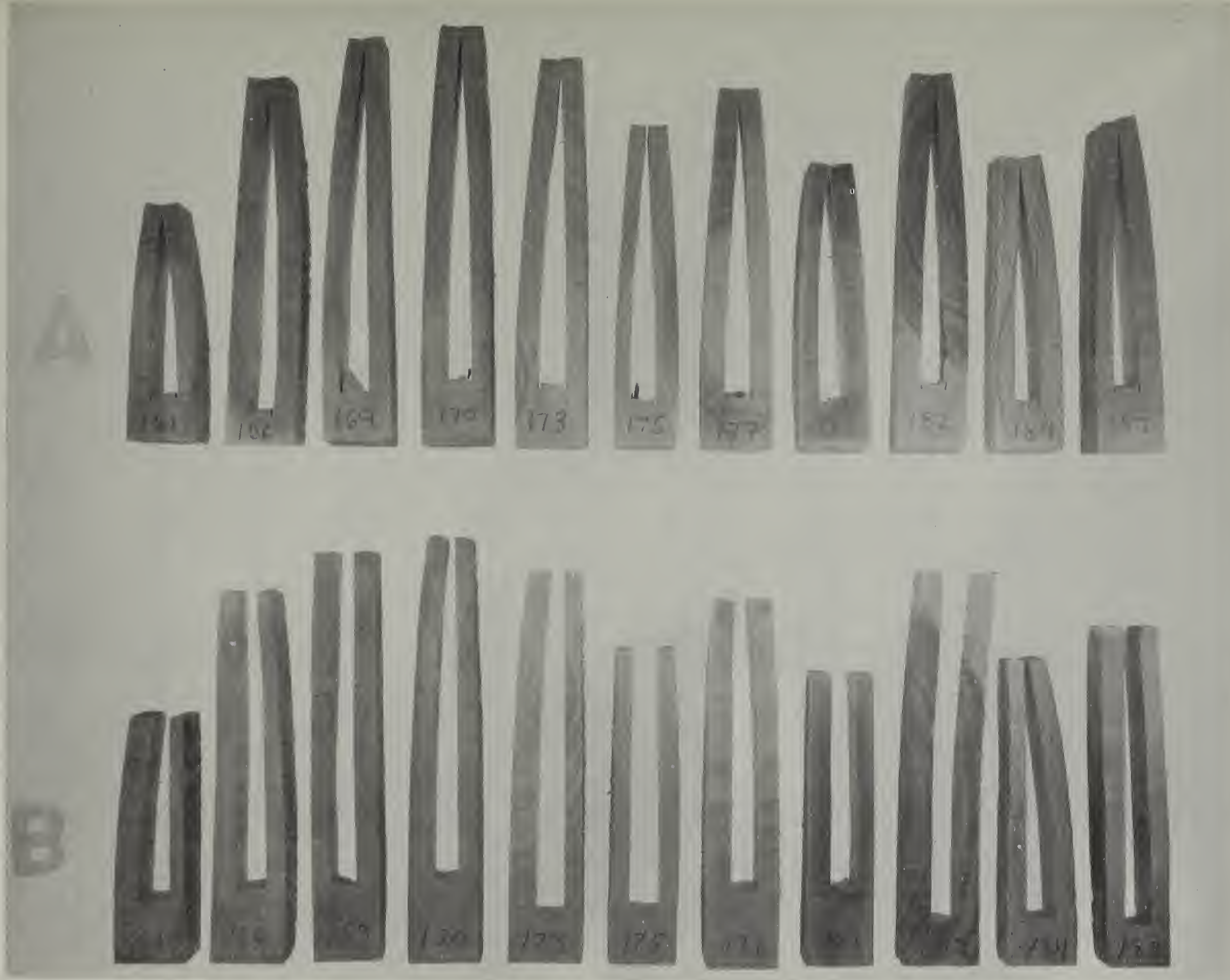

Figure 7.--Prong specimens showing severe casehardening (A) and stress relief after a 48-hour mist-spray conditioning period (B).

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Solar and air drying time of seven charges of Honduras mahogany of varying thicknesses and one mixed charge of 11 hardwood species has been determined. Results show that 1-, 1-1/4-, and 2-inch thick green mahogany can be solar dried to a final moisture content of 12 percent in 18, 25, and 41 days respectively. Mist spray conditioning removes casehardening. A moisture content of 15 percent can be reached in the solar dryer in one-half to one-fourth the time required for air drying with no sacrifice in quality.

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